

# Wolf-Rayet stars and GRB connection

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## Abstract

Arguments are given favoring possible connection of GRBs with core collapse of massive Wolf-Rayet stars. We analyze the observed properties of cosmic gamma-ray bursts, Wolf-Rayet (WR) stars and their CO-cores in the end of evolution. WR stars are deprived of their extended hydrogen envelopes, which makes it easier for the collapse energy to transform into observed gamma-ray emission. Presently, of  $\sim 90$  well-localized gamma-ray bursts, 21 ones are optically identified and for 16 of them redshifts are measured ( $z = 0.4 \div 4.5$ ). The observed energy of gamma-ray bursts spans over a wide range from  $3 \times 10^{51}$  to  $2 \times 10^{54}$  ergs. There is some evidence that this distribution  $N(\Delta E)$  is bimodal if take into account GRB980425 associated with a peculiar type Ic supernova SN1998bw in a nearby galaxy ESO 184-G82 for which  $\Delta E_\gamma \approx 10^{48}$  ergs. These characteristics of gamma-ray bursts are similar to the distribution of the final masses of CO-cores of WR stars which is also wide and homogeneous:  $M_{CO} = (1 - 2)M_\odot \div (20 - 44)M_\odot$ . A possible bimodality of the gamma-ray burst energy distribution ( $E_1 = 10^{48}$  erg;  $\Delta E_2 = 3 \times 10^{51} \div 2 \times 10^{54}$  erg) is in accord with the bimodal mass distribution of relativistic objects ( $M_{NS} = (1.35 \pm 0.15)M_\odot$ ;  $M_{BH} = (4 \div 15)M_\odot$ ). That the supernova SN1998bw is of the "peculiar Ic" type, atypical for WR collapses (type Ib/c), can be related to the rotation of the collapsing CO-core which can make the collapse longer and lead to the formation of a neutron star, the decrease of the gamma-ray burst energy, and the increase of the fraction of kinetic energy transported to the envelope. The expected collapse rate of CO-cores of most compact WR stars of type WO in the Galaxy is  $\sim 10^{-5}$  per year, which is only by one and a half order of magnitude higher than the average gamma-ray burst rate in one galaxy ( $\sim 10^{-6} - 10^{-7}$  per year). Two particular models that use WR stars as gamma-ray burst progenitors are considered: the hypernova model by Paczyński (1998) and the model of unstable CO-core collapse suggested by Gershtein (2000). In both models the allowance of a gamma-ray beaming or random outcome of the CO-core collapse due to some instabilities permits one to bring the rate of CO-core collapses in accordance with that of gamma-ray bursts. We argue that WR stars (most probably, of type WO) can be considered as progenitors of cosmic gamma-ray bursts. Two types of gamma-ray bursts are predicted in correspondence with the bimodal mass distribution of the relativistic objects. Three types of optical afterglows should appear depending on which CO-core is collapsing: of a single WR star, of a WR star in a WR+O or a hypothetical WR+(A-M) binary system. In addition, we briefly consider a model of gamma-ray bursts as a transient phenomenon occurring at early stages of galactic evolution ( $z > 1$ ), when very massive

( $M > 100M_{\odot}$ ) low-metallicity stars could form. Such massive stars should also lose their hydrogen envelopes and become massive WR stars whose collapses could be accompanied by gamma-ray bursts. WR-galaxies can be most probable candidates for gamma-ray burst host galaxies.

## Introduction

The principal requirements to the central engine of GRBs include (1) The ability to release the electromagnetic energy  $\sim 10^{52}$  ergs during 10-100 s (the typical duration of "long" GRBs, only for which X-ray and optical observations are possible; a separate group of short single-peak GRBs is much less studied, apart from the fact that they are isotropically distributed over the sky, and well may be another phenomenon) and (2) The event rate is on average about one burst per typical galaxy (assuming isotropy of the emission and homogeneity of galaxies) per  $\sim 10^7$  years. The beaming of gamma-ray emission decreases the energy emitted and increases by the same amount the event rate.

These requirements are met (with different degree of accuracy) by two broad classes of astrophysical sources. The first class includes coalescences of binary NS and/or BH [1]). The fireball is generated by neutrino-antineutrino annihilation copiously produced during the coalescence. The second class comprises models related to final stages of evolution of massive stars, among which:

- Collapses of massive stars [2, 3, 4]. An accretion disk is formed around a massive rotating black hole during late stages of the core collapse of a massive star; in this model, a narrow jet is produced inside the star and punches through the stellar envelope reaching very high Lorentz-factors.
- Electromagnetic model by V.Usov [5], in which the energy comes from the rapid rotation of a young neutron star (millisecond pulsar) with a very strong magnetic field. Other models in which magnetic field is crucial see in [6, 7].
- GRB during core collapse of a non-rotating Wolf-Rayet star by Gershtein [8], in which the internal shocks are created due to the collapse non-stationarity and energy is brought away by electron-positron plasma.

At the late stages of evolution, very massive stars lose their hydrogen-rich envelopes (via stellar wind or in a binary system) and are observed as helium-rich Wolf-Rayet (WR) stars. They are considered as progenitors of Ib type supernovae (if strong helium lines are present in the maximum brightness) or Ic supernova (if helium lines are weak or absent). If GRBs are directly related to collapses to massive stars, there should be some links between properties of WR stars before collapse

and GRBs. We suggest that observed broad (and, possibly, bimodal) distribution of GRB energetics is related (1) to the broad distribution of final masses of CO cores of *observed* WR stars before collapse and (2) to the *observed* bimodal distribution of masses of relativistic remnants of stellar evolution (neutron stars and black holes).

## GRB association with star formation

There is a growing evidence that cosmic GRBs are associated with star-forming regions:

- Optical observations of the identified GRB host galaxies evidence for an enhanced star formation rate inside the GRB sites, sometimes by an order of magnitude higher than in our Galaxy [9].
- Large column densities  $10^{22} - 10^{23} \text{ cm}^{-2}$  toward GRBs derived from known X-ray and optical afterglows of GRBs [10], typical for giant molecular clouds.
- Observed offset distribution of GRBs from their host galaxies statistically suggests association with the location of massive stars [11].
- Detections of line features in several GRB X-ray afterglows ([12] and references therein) imply a dense surrounding.

This favors GRBs association with evolution of massive stars and makes other GRB progenitors (such as double neutron star coalescences) less likely.

## Energetics of GRBs with known redshifts

Table 1 lists GRBs with known energetics. Photometric distances are calculated using a flat Universe with  $\Omega_m = 0.3, \Omega_\Lambda = 0.7, H_0 = 60 \text{ km/s/Mpc}$ . The Table also contains BATSE fluences (50-300 keV) and peak luminosities  $L_p$  phot/s (from [20]).

As seen from Table 1 and Fig. 1, 2, the observed GRB energetics spans from  $\approx 7 \times 10^{51}$  ergs to  $\approx 2 \times 10^{54}$  ergs. This observational fact is usually explained by a broad luminosity function of GRBs (see [22], [23]), although one can construct a self-consistent model with a universal energy release of  $E_0 \sim 5 \times 10^{51}$  ergs and a complex beam shape [24]. Adding GRB980425, which is possibly associated with peculiar type Ic supernova SN 1998bw in a nearby ESO 184-G82 ( $z = 0.0085$ ) [19], either evidences for a *bimodality* of GRB energy distribution or for an extremely broad luminosity function (more than 5 orders of magnitude!).

Table 1: GRBs with known energetics

GRB	$z$	$d_l^\dagger, 10^{28}$ cm	$F_\gamma, 10^{-5}$ erg/cm <sup>2</sup> (10-2000 keV)	Ref	$\Delta E, 10^{53}$ erg	$F_p^\ddagger$ ph/s/cm <sup>2</sup> (50-300 keV)	$L_p, 10^{58}$ ph/s
000926	2.066:	5.81	2.2	[13]	3.04		
000418 <sup>a)</sup>	1.118	2.73	1.3	[14]	$\sim 0.6$	-	
000301C <sup>b)</sup>	2.03	5.69	$> 0.05$	[15]	$\sim 0.07$	$\sim 5$	6.7
991208 <sup>c)</sup>	0.706	1.55	10	[16]	$\sim 1.8$	-	
990712	0.430	0.85	-				
990510	1.619	4.30	2.26	[17]	2.0	8.16	7.3
990123	1.6	4.25	26.8	[17]	23	16.4	14
980703	0.967	2.28	2.26	[17]	0.75	2.6	0.86
980613 <sup>d)</sup>	1.096	2.66	0.17	[18]	0.072	0.63	0.27
971214	3.412	10.6	0.944	[17]	3.0	2.3	7.4
970828	0.958	2.25	9.6	[17]	3.1	-	
970508	0.835	1.99	0.317	[17]	0.08	1.2	0.29
970228 <sup>d)</sup>	0.695	1.52	$\sim 0.2$	[18]	0.034	3.5	0.60
980425	0.0085	0.013	0.32	[19]	$7 \cdot 10^{-6}$	0.96	$2.1 \cdot 10^{-5}$

Notes:

 $\dagger$  Flat Universe,  $\Omega_m = 0.3, \Omega_\Lambda = 0.7, H_0 = 60$  km/s/Mpc $\ddagger$  Peak fluxes from [20]

a) Energy fluence in 25-100 keV;

b) Peak flux  $F_p = 3.7$  Crab, no fluence published, single-peak profile, duration 10 s; other indirect estimations of total energy in gamma-rays see in [21]c) Energy fluence for  $E > 25$  keVd) Energy fluence for  $E > 20$  keV

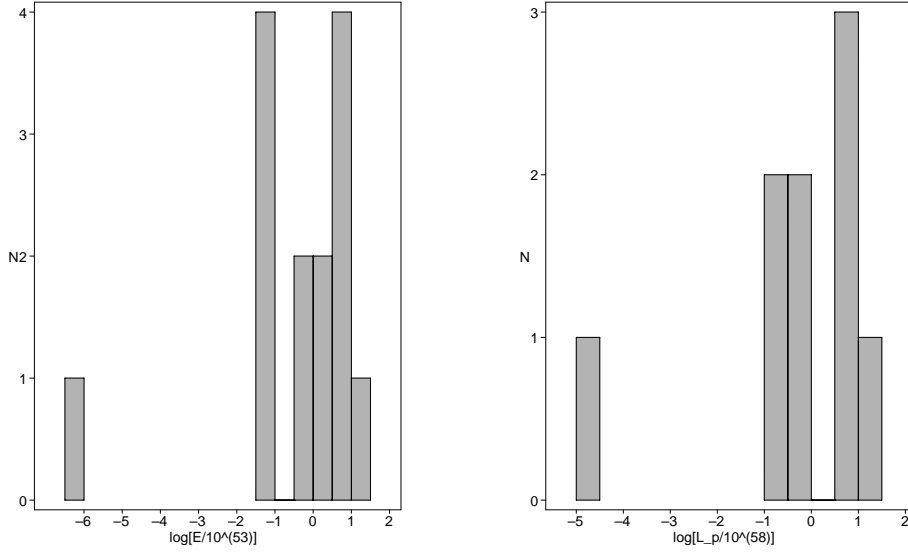


Figure 1: Total GRB energy release  $\Delta E$  (in  $10^{53}$  erg/s) of GRBs with known redshifts from Table 1

Figure 2: Peak luminosities  $L_p$  (in  $10^{58}$  phot/s) of GRBs from Table 1

□

Figure 3: Masses of final CO cores  $M_{CO}$  of WR stars as calculated using observed stellar wind mass loss  $\dot{M} \propto M^\alpha$ . Masses of known NS and BH candidates in binary systems are also shown.

## GRB and WR stars

The arguments favoring the link with WR stars are [25]:

(1) **Energetics** The observed GRB energy release  $\Delta E \simeq 10^{51} - 10^{54}$  erg is roughly comparable with the wide range of CO cores of WR stars before collapse,  $M_{CO}^f \simeq 2 - 40 M_\odot$ , Fig 3. The total energy released in collapse is  $E_G \sim GM_c^2/R_c$ , where  $M_c$  is the compact remnant mass,  $R_c$  its radius. During black hole formation in such collapses without mass ejection the available energy can reach  $10^{53} - 10^{56}$  ergs for the observed mass range of compact remnants, i.e. conversion of 1% of the available energy into kinetic energy of shocks with subsequent radiation would be sufficient to explain the broad luminosity function. Note that during collapse into black hole without mass ejection  $R_c \propto M_c \propto M_{CO}$  and available energy range is proportional to the CO core mass range, which is likely to be the case.

(2) **Bimodality of GRB energy distribution and stellar remnant mass distribution.** The known masses of NS and BH in binaries are shown in Fig. 4. NS masses are grouped in a narrow interval is  $M_{NS} = (1.35 \pm 0.15) M_\odot$ , while BH masses fall in a broader range  $M_{BH} = (5 \div 15) M_\odot$ . A real gap between NS and BH masses is observed.

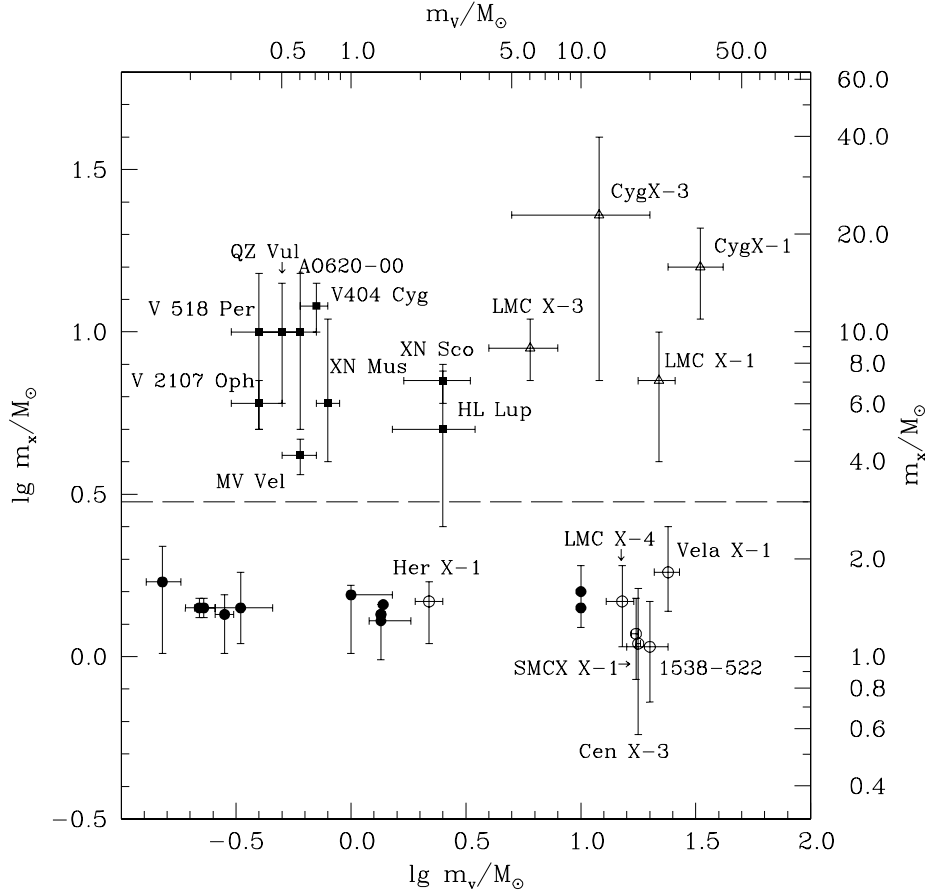


Figure 4: Dependence of the masses  $m_x$  of NS (circles) and BH (triangles and rectangles) on the masses of their companion stars  $m_v$  in close binary systems. Filled circles correspond to radio pulsars, filled triangles to BH in X-ray novae.

GRBs with low energetics associated with peculiar supernovae type Ic (such as GRB980425) can be explained by collapses of bare CO cores of massive stars with significant rotation which causes most envelope to be ejected and neutron star to be formed, while collapses of slower rotating cores do not accompanied by a significant envelope ejection and lead to black hole formation. In the latter case an energetic GRB can be generated with energy proportional to the pre-collapse core mass.

### (3) Association of GRBs with star-forming regions

(4) **A diversity of the observed afterglows** A GRB in a binary system can induce different optical phenomena due to illumination of the companion's atmosphere by hard X-ray and gamma-radiation [26]. This should add some light to the "pure" power-law afterglow from relativistic blast wave thus producing a great variety of the observed light curves. These effects can occur in a time interval  $\Delta t_{opt} > D/c$  after the burst ( $D$  is the distance to the optical star from GRB,  $c$  is the speed

of light). Deviations are indeed observed in some bursts (for example, in GRB980326 afterglow three weeks after the burst [27]).

Astronomical observations indicate [28, 29, 30] that about 50% of all WR stars in our Galaxy can be in binaries with O-star or A-M-star. For example, for WR+O system V444 Cyg with an orbital period of  $P = 4^d.2$  we have  $D \approx 40R_\odot$  and the time delay  $\Delta t_{opt} \approx 100$  s, and for parameters of WR+O binary system CV Ser  $\Delta t_{opt} \approx 300$  s. An extremely bright optical emission ( $V \simeq 9^m$ ) was observed in the famous burst GRB990123 only 50 s after the burst beginning [31].

Another example is a peculiar shape of achromatic optical afterglow light curve observed in GRB000301c [32, 21]. The observed several peaks separated by 2-3 days can be a manifestation of an orbital period in the underlied binary system, for example, through the binary-period shaped mass loss before collapse. An alternative explanation by a microlensing event [33] seems less probable. Orbital periods of order of several days perfectly fit the observed period range  $1^d.6 \div 2900^d$  in WR+O binary systems (see Table 2 in [25]).

These arguments favor the GRB-WR stars association, but there is a general requirement which should be met by all viable GRB models. The point is that GRB phenomenon should be an extremely rare astronomical event.

## Event rate problem

The GRB event rate per unit comoving volume using BATSE data with  $F_{tr} = 0.1$  ph/cm<sup>2</sup> [34] is

$$\mathcal{R}_{GRB} \sim 10^{-9} \text{GRB/yr/Mpc}^3,$$

i.e about  $10^{-7}$  per year in the average galaxy with a mass of  $10^{11}M_\odot$ . This is by several orders of magnitude lower than the total rate of core collapses associated with SN II and Ibc ( $\mathcal{R}_{SNIbc} \sim 3 \times 10^{-5}$ /yr/Mpc<sup>3</sup>, [35]). This discrepancy is usually eliminated by introducing a beaming of gamma-ray emission (e.g. [20]). It is not excluded that not each SN Ibc is associated with GRB for internal reasons.

The mean formation rate of all types of WR stars in the Galaxy is

$$\mathcal{R}_{WR} = R_\odot \frac{N_{WR}}{N_\odot} \frac{\Delta t_\odot}{\Delta t_{WR}} \sim \frac{1}{1000} \text{yr}^{-1}. \quad (1)$$

i.e. by a factor of 1000 exceeds that of GRBs. The most compact WR stars, so called WO stars, are much less frequent (3 out of total 200 are known in the Galaxy), so their formation rate is only by one order of magnitude higher than that of GRB. This issue can be solved either by postulating generically thin jets or, admitting quasi-spherically symmetric emission, by assuming the existence

of some "hidden" collapse parameters (rotation, magnetic field, etc.), which was suggested by [36] from an independent analysis of black hole formation in binaries.

In the hypernova scenario by Paczyński [3] the rarity of GRB phenomenon is also explained by requiring an extremely high magnetic field during core collapse of a rotating massive star into a  $10 M_{\odot}$  black hole.

In contrast, in the model of coalescing neutron star/black hole binaries (which is currently less favored by association of all observed GRB hosts with strong star forming regions, see above) the event rates varies from  $\sim 10^{-4}$  to  $\sim 10^{-6}$  per year depending on the binary evolution parameters [37], which is marginally consistent with the observed GRB rate and the event rate problem is not very strong.

## GRBs as a transient galactic phenomenon

There is another possibility to explain the observed association of cosmic GRBs with star-forming regions at high redshifts and their extreme rarity. GRBs may represent a transient galactic phenomenon occurring at the early stages of galactic evolution, like quasars and AGNs. It is established now [38] that at high redshifts  $z \sim 1-2$  a violent epoch of star formation in young galaxies occurred. It is also known that a lot of cold matter were bound in giant proto-galactic clouds at redshifts  $z > 2$ , which are observed as "Lyman-alpha forest" of absorption lines in quasar spectra. The formation of very massive stars  $100-500 M_{\odot}$  which final collapse into massive black holes took place at that epoch. Such massive star can not form from matter enriched with metals because of pulsational instabilities (see [39] and references therein). At low metallicity at the epoch of violent star formation, however, they could have formed. The possibility of energetic GRBs from collapses of such massive stars was studied in [40] with negative conclusion about their ability to produce an energetic GRB. But we note here that physical processes in such stars are still far from full understanding and potentially such stars could be GRB progenitors. The weakness of GRB980425 in a nearby galaxy can be a natural consequence of smaller upper masses of stars in regions of violent star formation at the present epoch.



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